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On tropospheric ozone and the tropical wave 1 in total ozone

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Abstract. Studies have shown that total ozone in the southern tropics exhibits a year-round stationary wave 1 pattern with maximum peak-to-peak amplitudes ~20-30 Dobson units (DU) during southern spring (September-October). The crest of this wave occurs in the south Atlantic region with largest amplitudes occurring within the months of intense biomass burning in South America and Africa from July-October. However, because the wave exists in all months of the year (weakest in May-June with peak-to-peak amplitudes ~10-12 DU), this indicates the presence of a persistent dynamical forcing mechanism. The present study investigates the persistence of the wave, combining ozonesonde data from several tropical stations with 14 years (1979-1992) of both Nimbus 7 total ozone mapping spectrometer (TOMS) ozone and National Centers for Environmental Prediction (NCEP) geopotential height analyses. The limited number of ozonesonde profiles in the tropics indicates that the primary contribution to both tropospheric column ozone and the TOMS ozone wave 1 lies in the low to middle troposphere, maximizing around altitudes 4-5 km. Near this maxima, 500 hPa (~5 km altitude) geopotential heights show a persistent (year-round) wave 1 pattern in the south Atlantic similar to TOMS ozone, indicating both equatorward transport of subtropical ozone into the region and a potential for planetary scale subsidence effects. This is the first study providing evidence that lower tropospheric ozone and dynamical transport have major roles in establishing persistence of the wave 1 anomaly in total ozone.

1. Introduction

Total column ozone measured from Nimbus-7 total ozone mapping spectrometer (TOMS) has been noted in several studies [*Fishman et al.*, 1991, 1992; *Kim et al.*, 1996; *Thompson et al.*, 1996; *Ziemke et al.*, 1996] to exhibit a zonal wave 1 pattern (maximum peak to peak amplitude ~20-30 Dobson units (DU) during southern spring) in the tropical south Atlantic region centered around 0° longitude. This wave persists throughout the year but maximizes during September-October at the time of intense biomass burning in South America and South Africa. *Ziemke et al.* [1996], using combined data from Nimbus-7 TOMS, NOAA 11 solar backscattered ultraviolet 2 (SBUV2), upper atmospheric research satellite (UARS) microwave limb sounder (MLS), and ozonesonde vertical profiles showed that most of the wave appears to originate in the troposphere.

Observations of ozone and ozone precursors (NO_x, CO, and hydrocarbons) during the GTE (Global Tropospheric Experiment) TRACE-A (Transport and Atmospheric Chemistry Near the Equator-Atlantic) and SAFARI (Southern African Fire Atmospheric Research Initiative) 1992 campaigns indicated that biomass burning products during southern spring are a source of tropospheric ozone in the south Atlantic region (see *Thompson et al.* [1996] and references therein).

However, the nature of tropospheric dynamics suggests that advection and convection processes also have an important role in forming the south Atlantic wave 1 in TOMS ozone. For example, the transport model used by *Krishnamurthi et al.* [1993, 1996] for October months suggested that tropospheric dynamics in the south Atlantic can produce an ozone peak in that region even in the absence of biomass burning. The conclusion was that the ozone maximum in October appears to be a manifestation of both horizontal and vertical advections and transport from regions of biomass burning.

The present study extends the investigation of *Ziemke et al.* [1996] by focusing directly on altitude distributions of ozone and dynamical variables. Ozonesonde profiles from several tropical stations are combined with National Centers for Environmental Prediction (NCEP) analyses, and TOMS version 7 ozone to associate tropospheric dynamics with the formation and year-round persistence of the south Atlantic wave 1 in total ozone.

2. Data

Total column ozone data used in this study are Nimbus 7 version 7 TOMS retrievals. In addition, standard daily (1200 UTC) NCEP geopotential height analyses were used to relate wave and wind structures to properties of the stationary tropical wave 1 in total ozone. For error reduction and consistency, these data were binned to equivalent 15° longitude by 5° latitude (85° S to 85° N) structures.

Ozonesonde measurements from several ground based

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tropical stations were used for this study, namely Ascension Island (8°S, 15°W), Brazzaville (4°S, 15°E), Natal (5°S, 35°W), and Samoa (14°S, 170°W). Seasonal means at Ascension Island for the March-April-May (MAM) season were estimated by averaging 16 profiles in 1991 and 1992. For the September-October-November (SON) season, 20 ozonesonde measurements were available. For Natal, 233 profile measurements from 1978-1992 were used in all, and for Brazzaville, 81 profiles were used spanning mid-1990 through October, 1992. Samoa data from April 1986 through January 1990 (published means and precision estimates by *Komhyr et al.* [1994]) were used to estimate tropospheric ozone in the vicinity of the TOMS wave 1 minimum (around 5°–10°S and 170°W).

3. Seasonal Structure of TOMS Tropical Wave 1

Figure 1 shows a longitude versus month climatology plot involving 14-years (1979-1992) of TOMS zonal anomalies (zonal means removed) averaged between the equator and 15°S (i.e., centered around the maximum of the south Atlantic wave 1 in TOMS ozone). The longitudinal structure seen is predominantly zonal wave 1 with maximum values each month at 0°longitude. Although maximum amplitudes are in September-October, the wave is clearly present in all months with a weak secondary maximum in March. Transport of biomass burning products from western and northern Africa may be the reason for this weak secondary maximum in TOMS ozone (see, for example, *Fishman et al.* [1992] and references therein). Smallest and largest peak-to-peak zonal wave amplitudes occur in May-June and September-October with values ~10 DU and 20 DU, respectively.

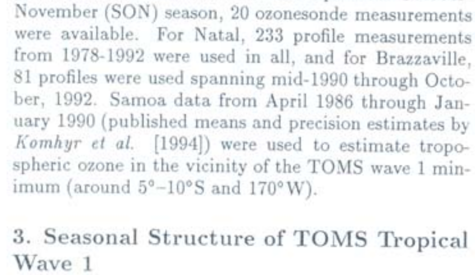

Figure 1. Climatological (1979-1992) zonal wave anomalies (zonal means removed) of version 7 TOMS total ozone averaged from equator to 15°S. Units: DU. Dashed contours: -1, -2, ... Solid contours: 0(dark), 1, 2, ...

An important question to answer is how such a sizable wave structure can exist year-round in TOMS ozone when most precursors (CO, NO_x, hydrocarbons) of tropospheric ozone formation caused by biomass burning in Africa and South America occur around July-October months (see *Thompson et al.* [1996] and references therein). Persistence of the TOMS wave 1 will be discussed further in section 5.

4. Tropospheric Ozone and the Wave 1

Figure 2 shows partial column ozone abundances at Ascension Island (left) and Samoa (right) for both MAM and SON seasons. Abundances measure column amount in 1 km vertical thicknesses. Hence, column amount between two arbitrary altitudes is given by summation of abundances between these levels.

Ascension Island lies very close to the maximum of the TOMS wave 1, and Samoa, located in the western Pacific, lies near the minimum. Tropospheric air at Samoa is relatively clean of ozone year round, in part because of upward transport of low levels of depleted boundary layer ozone. Contributions to column ozone in Figure 2 at both stations are largest around 2-5 km altitudes. Below these levels there is greater chemical destruction of ozone caused by mixing of ozone with surrounding air molecules, particularly in the low boundary layer where the e-folding lifetime of ozone may be only a few days.

Figure 3, similar to Figure 2, shows partial column abundances at Natal (Brazil) and Brazzaville (Congo) stations.. Both Natal and Brazzaville lie on the fringe edge of the tropical wave 1 maximum and do not show the strong MAM to SON seasonality seen at Ascension Island. Greatest contribution to column ozone again maximizes in the lower troposphere around altitudes 3-5 km. In all cases shown in Figures 2 and 3, largest contribution to total column ozone from tropospheric ozone lies in the low to middle troposphere, with maxima occurring around altitudes 3-5 km.

For completeness, Figure 4 shows Ascension minus Samoa abundance differences for the same MAM and SON seasons. This difference plot is important because it shows directly, as a function of altitude, zonal asymmetries present in tropospheric ozone lying between the western Pacific (minimum in TOMS wave 1) and south Atlantic (maximum in TOMS wave 1) tropical regions. The implication from Figure 4 is that largest contribution to the TOMS wave 1 comes mostly from the lower troposphere (largest station differences maximize in both seasons around altitudes 4-5 km). We note that above the tropopause (around 16-17 km altitude) differences are close to zero, indicating small contribution.

5. Stationary Dynamical Wave 1 in the Lower Troposphere

We have shown that greatest contribution to the TOMS wave 1 in both MAM and SON seasons lies in the lower troposphere around altitudes 4-5 km where tropical partial column ozone abundance maximizes.

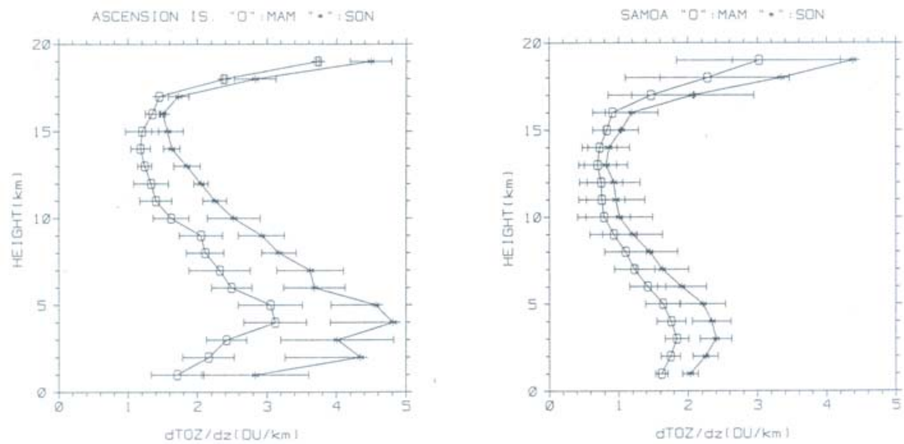

Figure 2. Partial column ozone abundances (units DU km^{-1}) at Ascension Island (left) and Samoa (right) for MAM and SON seasons (indicated). Horizontal bars denote ±one standard deviation.

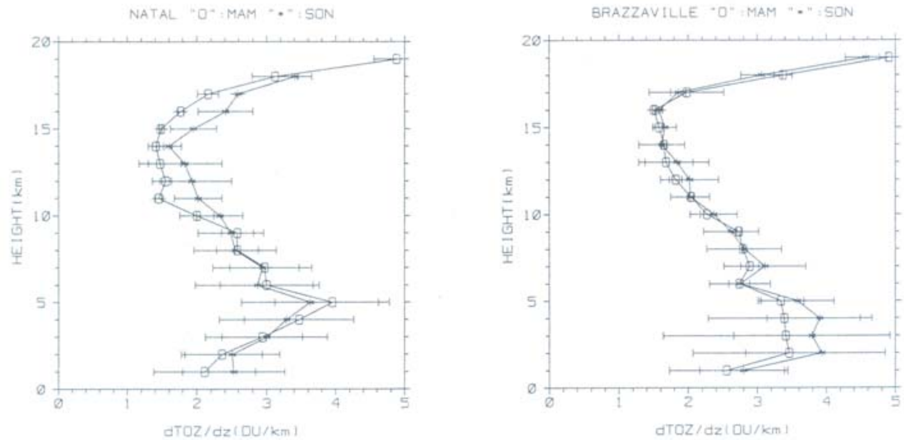

Figure 3. Same as Figure 2 but for Natal (left) and Brazzaville (right).

Having now derived this altitude range, we focus on geopotential height structures in the tropics around 5 km altitude in effort to deduce a plausible explanation for the observed persistence of the TOMS wave 1.

Figure 5 shows NCEP 500 hPa (~5 km altitude) zonal anomalies derived as in Figure 1 for TOMS ozone. Most apparent is a wave 1 structure, not as temporally smooth as with TOMS ozone, but nevertheless with corresponding maxima in the Atlantic region and a persistent month to month nature.

Even in low latitudes, monthly mean geostrophic winds provide an estimate of both the magnitude and direction of true wind fields. By definition, meridional (i.e., northward) geostrophic winds are proportional to the eastward gradient of geopotential heights and are thus independent of the zonal means subtracted from the data in Figure 5. Winds in Figure 5 will thus tend to flow equatorward where eastward gradients of 500 hPa heights are negative. That is, around 0°longitude, winds will generally flow equatorward, indicating year-round transport of higher latitude ozone (potentially high ozone mixing ratio) into the south Atlantic. The

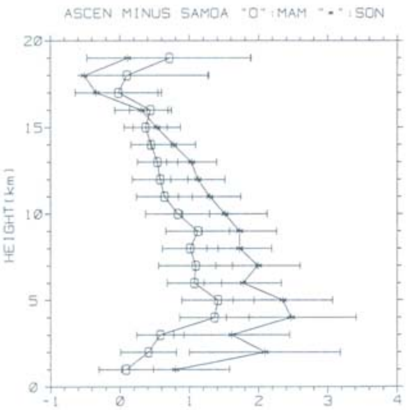

Figure 4. Ascension minus Samoa partial column ozone abundances for MAM and SON seasons (indicated). Units: DU km^{-1}. Horizontal bars denote ±one standard deviation.

positive height anomaly centered around 10° W to 15° W longitude also indicates possible sinking air in this region because the positive height anomaly at constant 500 hPa pressure corresponds to a positive pressure anomaly at constant height, potentially creating outflow of air mass and downwelling of air above.

The main result from Figure 5 is that the dynamical structure in the tropics near the altitude of largest contribution to the TOMS wave 1 shows a definite persistent wave pattern indeed similar to the TOMS wave 1. Corresponding winds transport higher latitude air mass (including ozone) equatorward into the region of the TOMS maximum year-round.

6. Summary

This study has examined ozonesonde partial column ozone abundances from several tropical stations in effort to first find out what region of the atmosphere contributes most to the TOMS tropical wave 1. Once finding this region, NCEP tropospheric geopotential heights were used to explain the year-round persistence of the TOMS wave 1.

Using ozonesonde measurements, we have shown that greatest contribution to the TOMS wave 1 lies in the lower troposphere around altitudes 4-5 km where tropical partial column ozone abundance maximizes. This has important implications for TOMS retrievals; apparently the TOMS instrument is capable of detecting much of lower tropospheric ozone.

The dynamical structure of 500 hPa (~5 km altitude) NCEP heights in the tropics indicates a definite zonal pattern similar to the TOMS wave 1. Corresponding winds transport higher latitude air mass equatorward into the region of the TOMS maximum year-round.

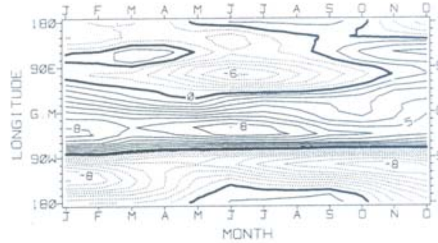

Figure 5. Same as Figure 1 except for NCEP 500 hPa geopotential heights. Contour increments are the same, except with units meters.

The nature of zonal wave patterns in both 500 hPa heights and TOMS ozone is (1) a strong wave 1 structure that (2) persists year-round. These similarities indicate persistent year-round dynamical forcing of the TOMS wave 1. Because biomass burning in Africa and South America is seasonal (~July-October), our results suggest that at least 10-15 DU of this wave anomaly in TOMS is attributed to year-round dynamical transport of ozone.

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